The summertime atmospheric hydrologic cycle over the southwestern US and northwestern Mexico

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1. Project Goals
We proposed an investigation of the US hydrologic cycle with a focus on the large-scale summertime hydrologic cycle associated with the southwestern branch of the North American monsoon.

2. METHODOLOGY: We are using a global to regional modeling system developed at the National Centers for Environmental Prediction (NCEP) to produce regional simulations of the summertime atmospheric hydrologic cycle in this region (**Fig. 1**). At present, continuous simulations of seasonal (July, August, September) hindcasts for the U.S. Southwest have been performed. The modeling system nests the 25km resolution RSM within daily forecasts from NCEP's global spectral model (GSM); these GSM forecasts are initialized using NCEP's operational analysis data. Importantly, the regional model produces explicitly-calculated sigma-level time-integrated diagnostic budget terms for the water vapor tendency equation. These budget terms will be used to analyze the important hydrodynamics of the system. To help with this analysis, we have also archived diagnostic terms related to the atmospheric hydrologic cycle derived from both reanalysis and observational data products. From the reanalysis, monthly values of the large-scale horizontal and vertical moisture flux divergence have been calculated from 1958-2002. In addition, we are presently obtaining sigma-layer moisture flux divergence estimates related to convective processes, including evaporative and precipitation values. Observationally, we have archived both the 1x1-degree monthly precipitation dataset available through GPCC and the 0.25x0.25 degree daily Unified precipitation dataset available through CPC. In addition we have estimates for large-scale 4xdaily moisture flux divergence values, calculated from radiosonde profiles throughout the domain. Finally, we will be archiving the LDAS evaporation estimates to compare with the vertically-integrated convective terms taken from the Reanalysis and the RSM.

3. RESULTS AND ACCOMPLISHMENTS:
3.1 GCIP Water and Energy Budgets
As part of the World Climate Research Program's (WCRP's) Global Energy and Water-Cycle Experiment (GEWEX) Continental-scale International Project (GCIP), Roads et al. (2002, 2003) developed a preliminary water and energy budget synthesis (WEBS) for the period 1996-1999

from the "best available" observations and models. Besides a summary paper (Roads et al. 2003), a companion CD-ROM (Roads et al. 2002) with more extensive discussion, figures, tables, and raw data is available to the interested researcher from the GEWEX project office, the GAPP project office, or Roads. An updated online version of the CD-ROM is also available at http://ecpc.ucsd.edu/gcip/webs.htm/. From this study it was concluded that observations cannot adequately characterize or "close" budgets since too many fundamental processes are missing. Models that properly represent the many complicated atmospheric and near-surface interactions are also required. This preliminary synthesis therefore included a representative global general circulation model, regional climate model, and a macroscale hydrologic model as well as a global reanalysis and a regional analysis. By the qualitative agreement among the models and available observations, it did appear that we now qualitatively understand water and energy budget budgets of the Mississippi River Basin. However, there is still much quantitative uncertainty. In that regard, there did appear to be a clear advantage to using a regional analysis over a global analysis or a regional simulation over a global simulation to describe the Mississippi River Basin water and energy budgets. There also appeared to be some advantage to using a macroscale hydrologic model for at least the surface water budgets.

3.2 Regional simulation of summertime precipitation

Using results taken from the fine-scale (25km), RSM simulation for the summer of 1999, along with contemporaneous daily surface observations, synoptic variations in climatological summertime precipitation over the southwestern United States have been described and analyzed by Anderson and Roads (2002). Two separate techniques for characterizing and evaluating large-scale summertime precipitation patterns within the observed and simulated systems are presented; in addition, these evaluation/characterization techniques are used to analyze the hydrologic forcings associated with observed and simulated modes of rainfall variability. Overall, two robust spatio-temporal precipitation patterns are identified (**Figs.2, 3**), involving: 1) precipitation over the western portion of the Rocky Mountain plateau centered on eastern Arizona and southern Utah and; 2) precipitation located over the eastern portion of the plateau and the elevated orography of eastern New Mexico and southern Colorado. Time-series associated with these two precipitation regimes are correlated with low-level and mid-level circulation patterns in order to investigate the related large-scale environmental conditions. It is found that for both regimes intraseasonal precipitation is related to the intrusion of mid-troposphere, mid-latitude low pressure anomalies over the southwestern US, resulting in synoptic-scale shifts in the position of the climatological mid-troposphere monsoon ridge. The interaction between the resultant mid-troposphere pressure fields and the quasi-stationary monsoon surface pressures found over the Rocky Mountain plateau during the summertime produce large-scale vertical velocities consistent with the observed and simulated rainfall patterns associated with each regime.

3.3 Regional simulation of intraseasonal variations

In addition, using results taken from these simulations, the summertime hydrologic cycle over the southwestern United States is characterized by Anderson (2002). Climatologically, the precipitation fields are balanced principally by the vertical diffusion of moisture into the column via evaporation, with only small contributions from large-scale moisture convergence via dynamic transport (**Fig. 4**). However, intraseasonal variations in the hydrologic cycle associated with the two spatio-temporal precipitation patterns points to a more complicated set of

hydrodynamic balances. Over the western portion of the Rocky Mountain plateau, columnar moisture divergence associated with precipitation is balanced by a combination of seasonal-mean convective moisture convergence and anomalous upper-air (> 4km) large-scale moisture convergence. The actual precipitating events themselves are predicated upon the anomalous upper-level advection of water vapor into the precipitating region; absent this large-scale advection at upper levels, vertical diffusion of moisture into the atmosphere balances large-scale divergence at mid-levels with little precipitation occurring. The anomalous large-scale advection during precipitating events is due primarily to anomalous large-scale vertical fluxes of moisture, with only a slight contribution from large-scale horizontal moisture fluxes. For precipitation located over the eastern portion of the plateau and the elevated orography of eastern New Mexico and southern Colorado, correlated moisture budget terms indicate that precipitation is again related to mean convective moisture convergence and anomalous mid-troposphere large-scale moisture convergence. As with the western-plateau precipitation regime, this anomalous convergence is strongly correlated with an anomalous vertical advection of moisture; however for the eastern plateau regime, this vertical term is the sole source of large-scale moisture convergence contributing to rainfall in the region. In both cases the vertical moisture convergence appears to be associated with the previously-mentioned intraseasonal modifications of the upper-level monsoon ridge centered over the Sierra Madres, which results in significant large-scale vertical velocities over the precipitating regions.

3.3 The summertime climatological atmospheric hydrologic cycle

In order to fully analyze the hydrologic cycle in this region, we have also collected appropriate observational datasets to compare with the large-scale reanalysis product (as well as fine-scale regional model output). At present, we have archived and analyzed the monthly and daily precipitation data taken from the Climate Prediction Center's (CPC) unified data archive, which is a daily, 0.25-degree resolution precipitation dataset spanning 55 years (1948-2002) for the continental United States. We have also archived and analyzed the 1x1 degree monthly GPCC dataset, which spans from 1996-2002. To help evaluate the atmospheric hydrologic cycle estimates from the two simulation products, we have produced estimates of the large-scale moisture flux divergence from the region using 4xdaily radiosonde profiles. In addition, we will acquire the LDAS evaporation estimates. We have begun evaluating the climatological characteristics of the analyzed and simulated precipitation fields. In addition, we have also begun evaluating large-scale diagnostic budget terms from the Re-analysis and observational products, using those calculated explicitly from the coarse-scale RSM modeling system.

A manuscript describing the large-scale climatological hydrologic cycle for the southwestern US is in preparation (Anderson et al. 2003). Preliminary findings indicate that over most of the southwestern United States and northwestern Mexico there is positive vertically-integrated columnar moisture divergence above approximately 700 mbar, implying that local convective activity provides much of the moisture for the monsoon precipitation. In addition, these findings suggest that the desert southwest is one of the largest upper-air (<700 mbar) sources of moisture for the continental US. We are investigating the variability of this hydrologic balance on synoptic to inter-annual time-scales.

3.4 RSM NAMIP simulations

1-day forecast simulations of the Southwest climatology are being developed with full budget implementation, for the period Sept. 27, 1997-present. In addition, continuous simulations are being developed to contrast how the regional model may improve certain aspects of the various simulations. Corresponding GSM 1-day and continuous simulations are being developed. Finally, we are developing continuous simulations with an upgraded version of the NCEP RSM, that are being used for participation in the NAME Intercomparison project.

PUBLICATIONS RESULTING FROM THIS RESEARCH

Anderson, B.T., J.O. Roads, H. Kanamaru, and M. Kanamitsu, 2003: The summertime climatological atmospheric hydrologic cycle over the southwestern US and northwestern Mexico, *in preparation*.

Anderson, B.T., 2002: Regional simulation of intraseasonal variations in the summertime hydrologic cycle over the southwestern United States. *J. Climate*, **15**, 2282-2300.

Anderson, B.T. and J.O. Roads, 2002: Regional simulation of summertime precipitation over the southwestern United States, *J. Climate*, **15**, 3321-3342.

Anderson, B. T. and J. O. Roads, 2003: The hydrologic cycle over the US Southwest. (in preparation)

Roads, J., E. Bainto, M. Kanamitsu, T. Reichler, R. Lawford, D. Lettenamier, E. Maurer, D. Miller, K. Gallo, A. Robock, G. Srinivasan, L. Luo, D. Robinson,V. Lakshmi, H. Berbery, R. Pinker, Q. Li, K. Vinnikov, J. Smith, T. von der Haar, W. Higgins, E. Yarosh, J. Janowiak, K. Mitchell, B. Fekete, C. Vorosmarty, T. Meyers, A. Grundstein, T. Mote, D. Leathers, and S. Williams., 2002a: GCIP Water and Energy Budget Synthesis. CD-ROM. (Available from International GEWEX Project Office)

Roads, J., R. Lawford, E. Bainto, E. Berbery, S. Chen, B. Fekete, K. Gallo, A. Grundstein, W. Higgins, M. Kanamitsu, W. Krajewski1, V. Lakshmi, D. Leathers, D. Lettenmaier, L. Luo, E. Maurer, T. Meyers, D. Miller, K. Mitchell, T. Mote, R. Pinker, T. Reichler, D. Robinson, A. Robock, J. Smith, G. Srinivasan, K. Verdin, K. Vinnikov, T. Vonder Haar, C. Vorosmarty, S. Williams, E. Yarosh, 2003: GCIP Water and Energy Budget Synthesis (WEBS). *J. Geophys. Res.* (in press)
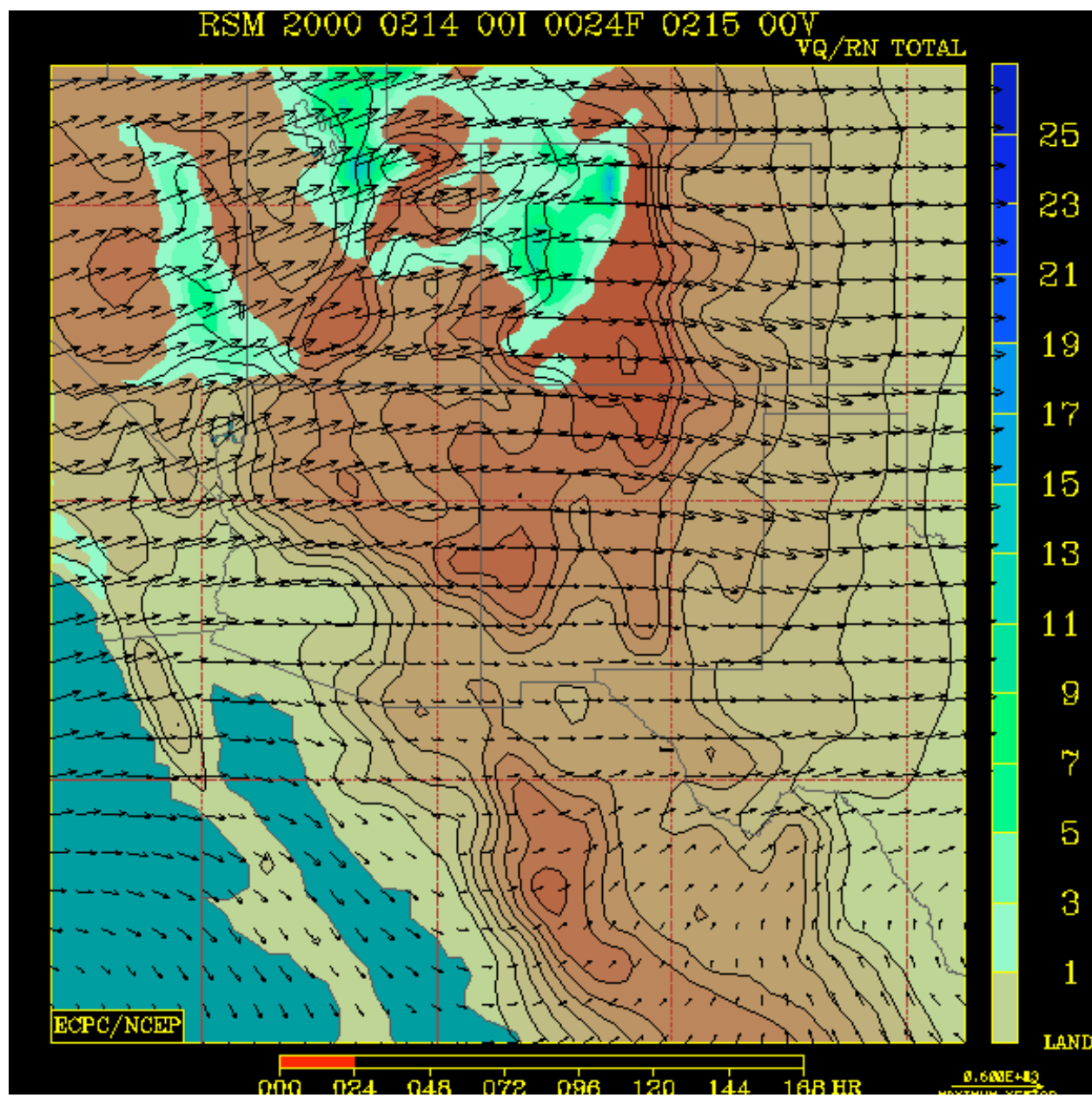
Fig. 1 SW model domain for experimental predictions. A 24 hour precipitation forecast valid 0215 00UTC. This model is run routinely at the Scripps Experimental Climate Prediction Center. Daily to seasonal predictions are provided at http://ecpc.ucsd.edu/

(a)

1st Canonical Factor Time-series

(b) OBS PRECIP

(c) RSM PRECIP
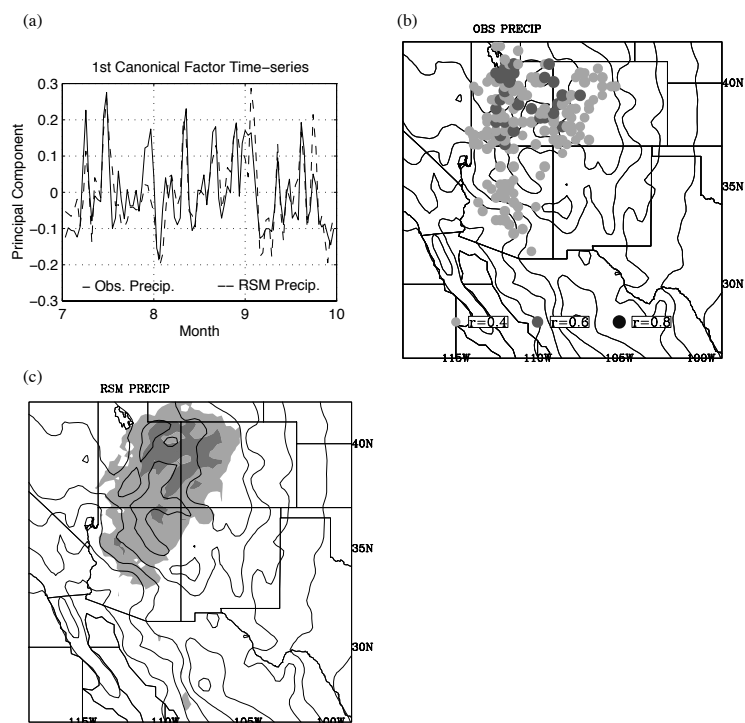
Fig. 2 a) normalized time-series of the first canonical factor of observed (solid line) and simulated (dashed line) precipitation. b) Grid-point correlations for the first canonical factor of observed precipitation. Shading interval is 0.2; minimum shading is 0.4. Positive values are shaded; negative values are black. c) Grid-point correlations for the first canonical factor of RSM precipitation. Shading interval is 0.2; minimum shading is 0.4. Negative values are not shown.

(a)

2nd Canonical Factor Time-series

(b) OBS PRECIP

(c) RSM PRECIP
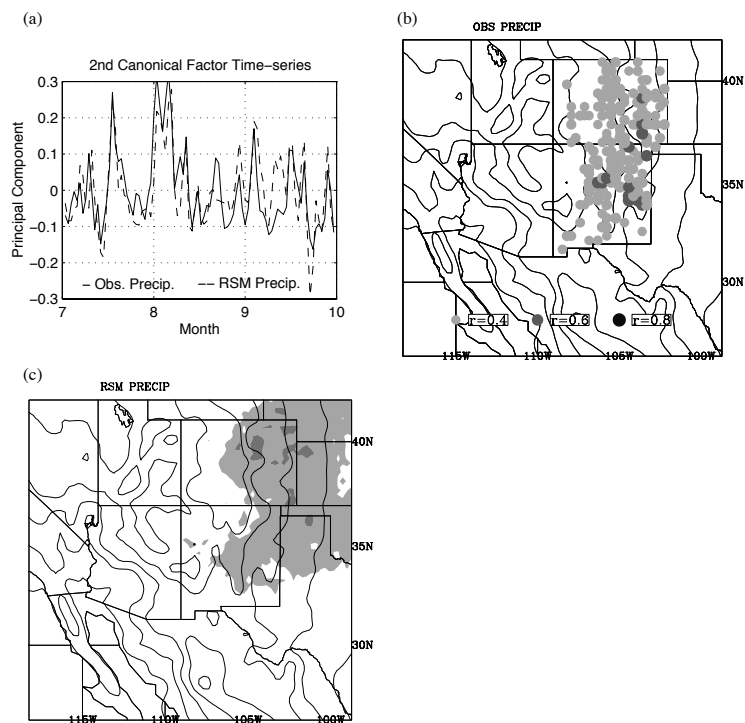
Fig. 3 Same as **Figure 2** except for second canonical factor of observed and simulated precipitation
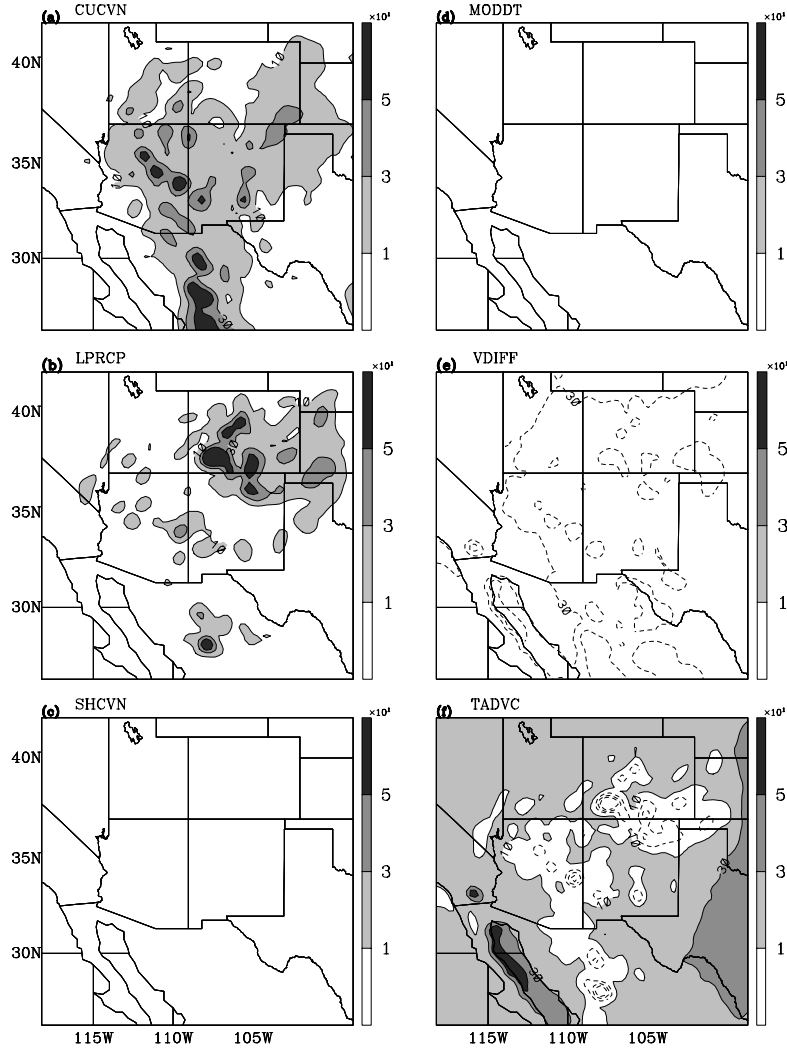
Fig. 4 Mean daily summertime (JAS) vertically-integrated RSM diagnostic moisture tendency terms. Shading interval is 20×10^{-6} kg m^{-2} s^{-1}; minimum shading is 10×10^{-6} kg m^{-2} s^{-1}. (a) convective precipitation; (b) large-scale precipitation; (c) shallow convective precipitation; (d) moisture tendency; (e) vertical diffusion moisture divergence; (f) large-scale total moisture divergence.